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Morphogenetic classification of the Arctic coastal zone

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Abstract Arctic coastal evolution is the result of interactions between exogenic and endogenic processes. In the arctic region, this evolution differs from that in other areas of the world's oceans as a result of interactions between modern wave and ice factors, and the influences of glaciations and large-scale sea level changes in the past. Geologic structure, origin and development determine contemporary relief morphology. Morphology appears to be the most significant relief characteristic, but it is controlled by a set of interactive processes active over long periods. Our approach, in which a multitude of interacting factors are simultaneously analyzed and determined, could be called "morphogenetic". We consider marine coasts and offshore zones (shelf) as a unit, and providing a general explanation for their evolution. The classification presented here is based upon the general approach given in the Science and Implementation Plan of Arctic Coastal Dynamics (ACD), a project of the International Arctic Science Committee and the International Permafrost Association. Our classification extends beyond the morphological ACD classification to include a morphogenetic classification.

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Introduction

The classification presented here is based on scientifically proven representations of morphology, origin and age as well as the geological and neotectonic provenance of coasts and seabed relief. This kind of approach, in which a multitude of interacting factors are simultaneously analyzed and determined, could be called "morphogenetic".

We define the coastal zone as "extending from the coastal plains to the outer edge of the continental shelves, approximately matching the region that has been alternately flooded and exposed during the sea level fluctuation of the Late Quaternary period", following the LOICZ Project definition (Coastal Zone Resources Assessment Guidelines 1996). Under "coasts" we understand an "onshore and coastal shallow that has been alternately flooded and exposed since middle Holocene time (climatic optimum)."

The proposed classification develops the Science and Implementation Plan of Arctic Coastal Dynamics (ACD) project approach. Morphology remains the most significant relief characteristic as per the ACD classification. However, relief morphology does not appear steady and changes with time. Analogous changes took place in the past, occur in the present and will continue in the future. As a result of climate warming, changes in relief morphology will be more active than at the present time. The main cause of changes lies in the fact that natural processes determine relief morphology and should be regarded together with relief morphology. In our classification, we attempt to distinguish the dominant natural process that resulted in the relief formation and its changes in the past and in the present. Some of the natural processes will intensify in the future, while others will moderate. In the context of such an approach, it is possible to ascertain future trends of relief morphology change. For instance, wave action during coastal formation, with intensification of abrasive processes, is currently increasing. As a result, the total extent of the abrasion sections of Arctic coast exceeds the length of the accumulation sections.

Knowledge of natural relief-forming processes is an important link in the system ‘‘land–ocean interaction’’, and must be taken into consideration in research of any scale. Indissoluble connections between natural processes and relief morphology exist. This connection is always observed: in research at larger scales for issues such as hazard assessment, climate change, etc., and within the framework of detailed analyses, including work in the context of the ACD project (coastal segmentation). This approach is an integral part of the ACD project for which there are indications that natural processes play a great role. In particular, ACD aims ‘‘to identify and understand the key processes controlling Arctic coastal dynamics and their impact on human systems, biology and ecosystems’’ and ‘‘to establish models to predict the future behavior of the Arctic coastal zone in response to climate and sea-level changes’’ (Rachold et al. 2003). Within the framework of the ACD Workshops, the coastal dynamics as a function of environmental forcing is constantly accentuated.

We regard marine coasts and the offshore zone (shelf) as a unit and provide a general model for their evolution. Accordingly, the principles of classification are the same for both regions.

The seabed is characterized by the predominance of the contemporary accumulative processes connected mainly to the processes of suspended load precipitation (normal sedimentation). These processes are controlled by currents, circular eddies, and extreme storms. Sedimentation under the ice in heavily glaciated regions (vast areas of the East Siberian Sea) plays an important role. The seabed surface is rather static with the exception of that of the Gorlo of the White Sea, Gorlo Cheshskoy Gyby and others, where the tidal flows are considerable. These processes play a less important role in relief formation in straits and in large estuaries.

Background, materials and methods

Earlier attempts at coastal classification had considerable gaps, since many forms and types of relief were not described and morphological features were emphasized. One of the first classifications, made by Richthofen (1901), is purely based on the morphology of the inner shelf. The most detailed classification was created by Schlüter (1924), in which he analyzed the peculiarities of the last (post glacial) sea level uplift in different geological situations in the context of the influence of climatic factors and high tides on coastal shaping in various zones of the world’s oceans. In the second part of the previous century, several marine coast classifications were developed by Valentin (1952), Zenkovich (1954), Leont‘ev (1956), McGill (1959), Ionin et al. (1961), Leont’ev et al. (1975), and Kaplin et al. (1991). A common disadvantage of the listed classifications is the high degree of generality, and all were intended for small scale mapping only. The variety of modern and paleogeographical processes in the Arctic are not reflected in these classifications, despite the fact that these processes distinguish the Arctic from other climatic zones. Furthermore, Arctic coasts and offshore zones were not analyzed as a unit, so that their regional peculiarities were not described in full measure, and their complicated history of development and the specific character of the dominant relief-forming processes were neglected.

At the same time ‘‘coastal zone’’ is interpreted as ‘‘extending from the coastal plains to the outer edge of the continental shelves, approximately matching the region that has been alternately flooded and exposed during the sea level fluctuation of the Late Quaternary period’’ (Coastal Zone Resources Assessment Guidelines 1996). This implies the necessity of a unified classification of the sea floor forms and the coast types based on uniform principles. In the classification presented here take into account processes and factors determining the type of sea coast as well as the morphology of relief forms. In addition, the evolutionary history was observed. It is stated that the development of the coastal zone in the Late Quaternary period was affected by the large-scale sea level fluctuations, which resulted in coastline migration along the shelf profile. Many forms of relief currently located below sea level, on the shelf, are genetically determined by the processes of coastal formation.

The morphogenetic approach enables us to accommodate the wide complex of interacting factors that simultaneously determine both the origin and morphology of different coastal relief forms.

The first and unique attempt at shelf form classification on the basis of morphogenetic principles was made by Ionin et al. (1990) more than 10 years ago. The role of the key relief-forming active and passive factors and processes, often in their complex interaction, was assumed as a principle. However, this classification disregards regional features of Arctic shelf relief formation. The proposed classification reworks the previous approaches with reference to the Arctic shelves.

The ACD project is a milestone in the preparation of such a classification. We have made an attempt to broaden the morphologic ACD classification and to bring morphologic relief characteristics in agreement with their genetic adjunct. That complies with the ACD project principles, which interpret coastal dynamics as a function of environmental forcing. This classification of the Arctic coastal zone that includes Arctic coasts and the seabed is based on long-term investigations.

In different years, our detailed multidisciplinary coastal investigations were conducted in the White Sea and on the Kola Peninsula, including the Barents coastal zone, in the fiords of Novaya Zemlya, in the Pechora and Kara seas, on the western coast of Yamal and in Baidaratskaya Guba, on Taimir Peninsula, along the Anabara-Olenek watershed coasts, in Olenek Bay and on the Lena Delta coasts, in Buor-Khaya Bay, on the island of Muostakh, on the New Siberian Islands coasts, in

Dmitry Laptev Strait, Kolyma Bay, and on the East-Siberian and Chukchy coastal zone. Investigations of the coasts were conducted both offshore and in coastal shallows, including inshore lagoons (Grigoriev et al. 2003; Rachold 1999, 2000; Rachold and Grigoriev 2001).

The main methods of onshore coastal studies are: (1) reviewing and reworking of both existing publishing and our own data; (2) field studies (the description of coastal relief morphology, measurement of coastal dynamics parameters as well as the investigation and sampling of geological and geocryological peculiarities of onshore outcrops); (3) processing and analysis of remote sensing material on the coastal zone (topographic and special thematic maps, satellite images and aerial photographs from different years). We use hydrometeorological observations, including measurements of wind and wave characteristics, as well as air and seawater temperatures (from the surface to the bottom) at the key sites.

Investigations in the offshore zone were conducted mainly on research vessels of small displacement, such as the "Professor Shtockman", the hydrographic vessels "Dmitry Laptev", "Maligin", "Vega", "Dunay", "Smirnitsky", and others. The bigger ships such as "Academic Sergei Vavilov", "Dmitriy Mendeleev", the icebreaker "Georgiy Sedov" and others (anchor stations and profiles on boats nearby) were used with modern instrumentation, including narrow-beam and multi-beam echo sounders, the "Parasound" profilograph, lateral view locators and samplers of different systems. During the last 5 years, detail field coastal studies within the framework of Russian–German expeditions were also conducted.

Details of much of this data collecting are available in the following cruise reports: White Sea (1962, 1964, 1965); Chukchy Sea (hydrographic vessels "Dmitiy Laptev" and "Maligin"—1978, 1981); East Siberian Sea (ice-breaker "Georgiy Sedov"—1981), Barents and Kara Seas—(eighth, tenth, 12th, 19th cruises of r/v "Professor Shtockman"—1982, 1983, 1984, 1988); Kara Sea (41th cruise of r/v "Dmitriy Mendeleev"—1993); the Pechora Sea (13th cruise of r/v "Academic Sergey Vavilov"—1998). All of the listed cruise reports are available from the Shirshov Institute of Oceanology (IORAS) in Moscow.

Results and discussion

The Arctic coastal zone occupies a special place in the world's oceans. The climate strongly affects not only the character of modern coast-forming processes but also mobilization, transfer, and sedimentation in the coastal zone. Initial structures form the basement surface that has been reworked, or is now being reworked, by a complex of environmental processes. Among exogenic and endogenic processes it is possible to identify *active processes*, directly participating in the formation of coastal relief, and *passive processes*, which predetermine the display of active ones and direct a course for their development.

This work attempts to develop the concept that the origin of the relief (formed under the interaction and combination of various modern and paleogeographical processes jointly with geological provenance) was the most important factor in creating extant coastal morphology.

Morphological *coast types* could be characterized as landscapes that form under a unique combination of modern, paleogeographical and geological conditions (Table 1). *Coast types* are composed by the combination of *forms of relief* from a sequence of modest length. Such a combination of *coastal forms* determines the general appearance of each *coast type* and reflects the interaction of the main relief processes that, due to coast type, currently exist. For instance, the coast type, "fiord", is, in fact, rather a long coastal area within which occur a number of different *coastal relief forms*, such as: cliffs unchanged by the sea, abrasion–denudation coasts, ice coast, moraine taluses, etc. These combinations of coastal forms lend the fiord landscape its unique appearance. Depending on their specific origin and evolution, coast types are characterized by their own combination of coastal relief forms.

Specific coast types arise from the main relief processes that take part in their formation. For example, the coast type "fiord" was mainly created under tectonics jointly with ice exaration and erosion processes. The coast type "accumulative with lagoons" arose via wave processes during recent (Late Pleistocene—Holocene) sea level uplifting and via modern processes (other types have had polygenetic origin).

Dominant relief processes and their development are the result of interactions between endogenic and exogenic processes. In any particular situation we could determine the dominant factor governing coast formation. These dominant factors could be (1) structural (endogenic), (2) structural–sculptural (endogenic–exogenic), and (3) sculptural (exogenic) (Table 1).

The classification presented here is based on the general approach given in the ACD, which is a project of the International Arctic Science Committee and the International Permafrost Association (IASC Arctic Coastal Dynamics 2001). However, in addition to the morphological classification suggested by the ACD project, the classification suggested in this present paper considers interactions between coastal morphology and dominant factors (processes) governing coast formation. For example, within the framework of the ACD project, studies of detailed morphological characteristics of coastal sections have been carried out. At present, a distinction has been made for abrasive–cryogenic coasts of the Laptev Sea, which, in our classification, appear as a unique coast type from a genetic point of view. We hold that the combination of major morphological features justify a classification of abrasive–cryogenic coasts in general and of coastal relief forms in particular. The coastal gradations listed in Table 1 could be expanded

Table 1 Morphogenetic classification of arctic coasts

Dominant factors governing coast formation	Active relief processes (origin)	Morphological types of coast	Prevailing morphological forms of coast	Examples
1	2	3	4	5
Structural	Created by tectonics with insignificant marine influence	Primarily straightened		Pronchischev Coasts (Taimir Peninsula)
		Overflowed		Murmansk Coasts of Kola Peninsula
Structural–sculptural	Created by tectonics with exogenic modification	Dissected by glacial-tectonics (fiords) or glacial-exaration (fiards) slope treatments	Crumbled under denudation processes	Island of Novaya Zemlya—southern and northern coasts of Bay of Mashigin; Norwegian fiords
			Rocky	Slopes of Norwegian fiords
			Icy	Borzov Bay (Novaya Zemlya Isl.)
			Ice accumulative (moraine talus)	Bay of Mashigin-Ledyanka, (Novaya Zemlya Isl.) in area of coastal glaciers tongues
		Skerry type coasts	Sheep-back rock	Kola Peninsula between Lunbovskiy Bay and Ponoy River; Taimir Peninsula
			Ice-dressed rocks	Taimir Peninsula northern sector; Nordensheld Isl.
Sculptural	Created by modern wave processes	Abrasive-accumulative and straightening	Abrasive	Widespread areas
			Abrasive-accumulative with bays	Capes of Dezhnev, Ikigur, Heart-Stone, Jenretlen and others (Chukchy Sea)
			Abrasive-accumulative straightening	From cape Shelagsky to cape Yakan (East-Siberian Sea)
			Accumulative	Zemlya Bunge Isl. (East Siberian Sea)
	Jointly created under sea level uplifting and modern processes (polygenetic)	Accumulative with lagoons	Bars and lagoons	Chukchy Sea
	Jointly created by cryogenic and modern wave processes	Abrasive-Cryogenic	Thermal abrasive	Muostakh Island, Laptev Sea
			Thermal denudative	Western coast of Yamal Peninsula
		Abrasive-Cryogenic	Thermal abrasive – Thermal denudative	Bykovsky Peninsula, Laptev Sea
			Thermoabrasive – accumulative	Western coast of Shirokostan Peninsula
			Thermoabrasive – solifluctive	West coast of Byor-Khaya Peninsula (Laptev Sea)
	Created by tides	Laidas, Marsches	Laidas, Marsches	Morjovets Isl., Nothern coast of Shirokostan Peninsula
	Created be fluvial processes (potamogenic) and modified by cryogenic and modern wave processes	Deltas	Alluvial-accumulative	Eastern Lena Delta
			Erosive and thermoerosive	Northern Lena Delta
			Abrasive-accumulative	Example, Western coast of the Lena Delta
	Created by sea ingression into river mouths	Limans	Limans	Koluchinskaya Bay (Chukchy Sea)
	Created by glacial covers outside the fiord areas	Icy	Icy	Island of Franz Jozef Land
	Created or modified under industrial activity	Technogenic	Constructive	Coast with various types of protective constructions, berths, etc.
			Destructive	Open cut mines, etc.

through the addition of detailed morphological characteristics of coastal relief forms (cliff height, beach width, etc.). These data could be reflected as a separate column in the table. Morphological parameters identified in the ACD Project, including onshore, backshore, frontshore and offshore zone (Table 2) parameters, could be listed in these additional columns. The presented classification permits mapping at different scales. Mapping at a smaller scale could consider morphological coast type characteristics only (such as: fiord or fiard-type shoreline, lagoon-type coast, etc.). On the other hand, the classification could be expanded by additional data through continued subdivision of gradations.

The engineering-geocryological zonation of the Arctic coast could be integrated into this classification system as well. One of the major goals of zoning is an assessment of the intensity of exogenous geological processes along the Arctic coast. This assessment is a basis for the assessment of hazards for industrial activity on the Arctic coast (construction of pipelines, oil and gas terminals, etc.). The Arctic coastal zoning enables one to associate the major morphogenetic coastal types as classified here with the main varieties of rocks composing the coast (Table 3).

The methodological basis of Arctic coastal zoning consists of: (1) the generalization of major coastal types selected from the morphogenetic classification; (2) their correlation with modern engineering-geocryological conditions on the Arctic coast; (3) a detailed segmentation of the Arctic coast.

We generalized three main morphogenetic coastal relief forms at a scale of 1:8,000,000: abrasive, accumulative, and stable (Table 3). Most of the coast is composed of frozen, scattered rocks. Their transformation by the sea and by exogenous geological processes depends to a significant extent on their ice content (low ice content, moderate ice content, or ice-rich). In addition, 26 engineering-geological regions were identified. The tables listing these zones is, in fact, a legend to the Arctic coastal zoning map at a scale of 1:8,000,000 (Rivkin et al. 2003).

The main principles of coastal morphogenetic classification correspond to the principles of the morphogenetic classification of Arctic coastal offshore zones. Using the same approach, we identified three broad categories of seabed relief: structural, structural–sculptural and sculptural. Such a division is rather relative in some cases. We understand that the offshore zone forms under the joint influence of endogenic and exogenic processes. Extensive marine studies are required to include seabed relief. It is necessary to determine the dominant factor governing seabed formation.

We also allocated structural and sculptural relief and its morphogenetic divisions somewhat subjectively. For example, geologists usually try to examine existing seabed relief from structural provenance only while specialists in paleogeography and modern processes, on the other hand, consider seabed origin mainly in association with exogenic processes.

Table 2 Example of unified ACD and morphogenetic classification of arctic coasts (could be modified depending on mapping interests)

Dominant factors governing coast formation	Active relief processes (origin)	Morphological types of coast	Prevailing morphological forms of coast	Cross-shore zones	Section morphology	Methods and types of measurements	Latitude and longitude
1	2	3	4	5	6	7	8
Sculptural	Jointly created by cryogenic and modern wave processes	Abrasive-Cryogenic	Thermal abrasive	Onshore	Form—code Relief Sediments		
				Backshore	Form—code Relief Sediments		
				Frontshore	Form—code Sediments		
				Offshore	Form—code Relief Sediments		

Table 3 Engineering-geological zoning of the Arctic coast

Coasts	Rocks and sediments composing the coast							
	Rocks	Unfrozen ground	Frozen ground			Combination of rocks and		Ice
			Low ice content	Mid-ice content	High ice content	Unfrozen grounds	Low ice content frozen ground	
Abrasion	No. of the engineering-geological areas							
Abrasion	1							
Thermal abrasion			2	3	4			
Coastal ice								5
Thermal-denudation			6	7	8		9	
Abrasion-accumulative		10	11	12	13		14	
Accumulative								
Lagoon and liman-lagoon			15	16				
Laidas		17	18	19				
Deltas		20	21	22	23			
Stable								
Fauld, fiord, and skerry	24					25	26	

We have tried to analyze all interacting factors with minimal bias. From this point of view, it is better to create seabed characteristics in a ''layer by layer'' fashion. For example, four layers might be created thus: bathymetry; endogenic background; relief connected with the action of paleogeographic factors; relief caused by the action of modern processes. The necessity of a ''layer by layer'' method for assembling relief characteristics arises inevitably from the creation of such specialized maps (geomorphological, etc.). For example, if we combine bathymetry (first layer), geology (second), paleogeography (third) and modern processes (as the last layer), we create a geomorphological map. Using this combination, it becomes possible to create other maps and schemes.

Turning back to our classification, we treat almost all structural forms as large seabed forms, predetermined by geological structures and created by endogenic processes (i.e. by folded and fault-fracture tectonics, displays of the most recent differential vertical movements of the earth's crust and so on). Geological structures underlay practically all forms of seabed relief and determine the positions of its large forms. Relief created under the domination of tectonics could be divided into several types generated within anticlines and brachyanticlines, synclines and brachysynclines, monoclines and flexures, faults and fault-blocks (graben valleys), horsts and fracture-block zones (Table 4).

Structural–sculptural relief refers to a category of transient and in some cases relict formations. These relief could be divided into: (1) large troughs frequent with ''stairs'' of inset erosive-accumulative terraces created by paleo-flows into large structural valleys; (2) landslides, blocks and ridges near to the shelf edge and on the continental slope, swells in the coastal zone, landslide cones and cirques within canyons, fiords and depressions, created by gravitation processes on steep structural slopes; and (3) fiords and underwater trough valleys continuing them created by tectonics with exogenic modification (Table 5).

The sculptural relief of the Arctic seabed could be divided into several types too, which are listed in Table 6.

Table 4 Structural coastal seabed relief created under dominance of tectonics

Active relief processes (origin) 1	Types and forms of seabed relief 2	Natural examples, regions of distribution 3
Created by tectonics within anticlines and brachyanticlines	Raisings-islands, the shallow banks, the extended ridges and swells	Franz Josef Land archipelagos, Wrangel Island, Gusinaya bank in the Barents Sea, Gerald bank in the Chukchy Sea
Created by tectonics within synclines and brachysynclines	Extended troughs, depressions and shallow depressions	Long Strait, the Central-Chukchy depression, Southern Barents Sea depression
Created by tectonics within monoclines and flexures	Extensive horizontal plains	Part of the Kara Sea shelf to the north of Ob and Yenisey estuaries
Created by tectonics within faults and fault-blocks (graben valleys)	Graben valleys, inter-island channels	Medvezhinskij, Franz Victoria, George, St. Anna, Voronin, Sedov troughs
Created by tectonics within horsts	Underwater elevations, separate islands as ''Farewell Rock''	Structural-block raisings (Murmansk, Central, Persey), overfault-block raising of Gusinaya bank in Barents Sea

Table 5 The structural – sculptural coastal seabed relief created under dominance of tectonics and exogenic processes

Active relief processes (origin) 1	Types and forms of seabed relief 2	Natural examples, regions of distribution 3
Created by paleo flows into large structural valleys	Large troughs, frequently with "stairs" of inset erosive-accumulative terraces	Chukchy Trough
Created by gravitation processes on steep structural slopes	Landslides, blocks and ridges near to shelf edge and on continental slopes, swells in coastal zones, landslide cones and circuses within canyons, fiords and depressions	Fiords of the Northern Norway and Novaya Zemlya Isl., Beaufort Sea canyons
Created by tectonics with exogenic modification	Fiords and underwater trough valleys continuing them	Fiords of Northern Norway, Novaya Zemlya Isl.

Hydrodynamic relief created by wave processes has the greatest variety. This type of relief is distributed throughout all of the seas and oceans. In the Arctic, however, and especially in seas covered with ice for most of the year, the coastal shallows form under the combined influences of wave action and ice cover. Ice cover sharply weakens the intensity of waves and leads to the accumulation of fine deposits even in the coastal shallows and to the formation of a gently sloping coastal profile on the inner shelf. Such coastal shallows, which evolve not only via wave processes but also with an ice cover, we term an "Arctic type of coastal shallow". They form under the influence of both waves and the ice factor, manifesting a vivid example of modern lithological–geomorphological processes in the Arctic coastal zone.

Relic relief created by wave processes (abrasive and accumulative) is represented by ancient coastlines, which are fixed by terrace ledges generated during post-glacial time, as ancient barrier spits, bars and underwater swells flooded and frequently buried under a layer of younger marine deposits. For example, some relic bars are situated on the East Siberian seabed between the river mouths of Kolyma and Indigirka, and within offshore New Siberia and Zhokhov Islands also. Their thickness on the shelf surface ranges from 4–5 to 10–13 m and they extend from 15–20 to more than 40 km (Nikiforov 1996).

The tidal relief on the Arctic sea shelves, as well as in all other climatic zones, is represented by extremely modern formations, among which tidal ridges, sandy waves, tidal deltas, troughs, and mud flats are widely distributed. In the southern part of the White Sea Gorlo, they achieve a thickness of 30 m over the bottom of the largest tidal accumulation ridges, and their length is more than 40 km at a distance of 10–30 km between ridges. The characteristic element of accumulative relief on tidal shelves are watts, i.e. regions leveled or dissected to some degree by drain trenches, mud or sandy surfaces, and which are drained periodically by tidal fluctuations in sea level. Destructive tidal forms of relief are over-deepened inter-island channels, trenches in barrier-spit channels in lagoons.

Relic relief created under the joint activity of glacial covers and fluvial processes (relic fluvioglacial relief) are represented by channels of sub-glacial snowmelt flows, relatively level surfaces of outwash plains, kames and eskers, and are distributed on shelves of the Northern Atlantic and in parts of the Barents and Kara seas. Channels of sub-glacial snowmelt flows are usually expressed by narrow V-shaped ruts and hollows with incision depths of about 10–50 m and lengths in the tens of kilometers. Accumulation surfaces of the outwash plains, usually comprised of sand, gravel and pebbles, represent the merged fields of flat cones of fluvioglacial streams and are located in front of end moraine ridges. They are distributed on the surfaces of plateaus in the Greenland, Iceland, and Norway shelves and are also found in the mouths of fiord bays in the northwest portion of the Kola Peninsula.

Relief created by fluvial processes only is represented by relic (paleo-valleys, paleo-deltas, etc.) and modern (river deltas, etc.) forms. Not all relic, eroded valleys were subsequently filled by glacial-marine Quaternary deposits. Some of them persist as flat depressions in the shelf relief, and are often discovered by seismo-acoustic profiling. Quite often these depressions bear dendritic networks almost from the coast up to the shelf edge. In the eastern Eurasian Arctic shelf, in the Laptev, East Siberian and Chukchy seas, the systems of fluvial paleo-valleys are etched in regions around the modern mouths or deltas of the Khatanga, Anabara, Lena, Yana, Indigirka, Kolyma, and Amguema rivers and others. These valleys often terminate in paleo-deltas at depths of about 50 m, which were generated in subaquatic conditions as occurs in the Hope paleo-valley (Chukchy Sea), which has a width of about 30 km. In this area, paleo-deltas are found at depths of 50 and 35–40 m and have been dated with absolute ages of 17,000 and 12,000 years, respectively (Creager and McManus 1967). Paleo-valleys of the Yukon, Anadyr and also Chaplin rivers (as well as others) exist on the Bering Sea shelf, while paleo-valley networks connected with paleo-channels of the Ob and Yenisei rivers occupy the Kara Sea shelf. Recently discovered canyons of the Bering Sea, such as St. Matthew and Middle, with great numbers of tributaries have an erosive origin, too. Middle canyon is distinguished by numerous inflows. Canyon top formation is associated with the paleo-valleys of the

Table 6 The sculptural coastal seabed relief created under dominance of exogenic processes

Active relief processes (origin)	Types and forms of seabed relief		Natural examples, regions of distribution
	Relic	Modern	
Created by glacial exaration (destruction) of ice covers, moving pack ice and icebergs	Bottoms of fiords, landscapes of the "roches mountonnees" (scarrys)	Grooves, deflection (drag) furrows created by moving pack ice and icebergs	*Relic*—fiords of the Novaya Zemlya Isl., Spitzbergen Isl, Northern Norway, the Nordensheld archipelago (Kara Sea). *Modern*—grooves, ice deflection furrows on the shelves of Beaufort and Baffin seas.
Created by glacial-accumulative processes	Ridges and hills of side and end moraines, drumlins	Side and ground moraines, push swells and ridges generated by fast ice and icebergs	*Relic*—moraines at Northern Norway coast ("Egg moraine"); drumlins in Hudson gulf. *Modern*—moraine ridges in fiords of the Novaya Zemlya archipelago, on a shelf of Spitzbergen and Greenland, push swells in the Beaufort Sea, etc.
Created by subglacial (under ice cover) sediment accumulation	Buried accumulative plains	Coastal accumulative plains	*Relic*—depressions in the Barents Sea, Kara sea *Modern*—East Siberian Sea
Created by thermokarst (cryogenic) processes	Depressions of melting lenses of repeatedly-cavern-load ice filled by Holocene marine deposits	Depressions with abrupt boards	*Relic*—Chukchy, Laptev seas, etc. *Modern*—Laptev, East Siberian seas
Created by cryodislocative (cryogenic) processes	Are not known	Folds, frost mounds	Coastal zone of the Western Yamal
Created by wave abrasion	Surfaces and ledges of underwater terraces, abrasive farewell rocks and ridges, abrasive plains	Modern cliffs and benches	*Relic*—the Pechora Sea, Kara Sea, Laptev Sea, etc. *Modern*—everywhere within modern inner shelf and shoreline zone
Created by wave accumulation	Ancient underwater accumulative forms (submarine bars, etc.)	Modern coastal accumulative forms (barrier islands, spits, barrier spits, terraces, beaches etc.), underwater swells	*Relic*—buried bars on the shelf near the Novosibirsk Isl. *Modern*—everywhere within modern inner shelf and shoreline zone
Created under combined influences of wave action and ice cover on the inner shelf	Not found	Gently sloping coastal profile on the inner shelf with accumulation of fine deposits	East-Siberian inner shelf
Created under influence of normal sedimentation processes and long term accumulation outside of wave activity zone and without influence of strong permanent currents	Ancient buried plains	Accumulative plains	*Relic*—Central Depression in the Barents Se *Modern*—Kara Sea, Laptev Sea (western areas), etc.
Created by tides	Not found	Sandy waves and ridges, mud flats, tidal troughs, overly deepened channels of lagoons, step tidal benches	Coastal areas with high tides value (Northern, Barents, White seas)
Created under influence of strong currents	Not found	Erosive plains generated in conditions of powerful permanent currents	Central part of Bering Strait
		Seabed accumulative cones generated under fast sediment unloading	Adjoining areas to Bering Strait at the southern part of Chukchy Sea
Created by fluvial processes	Channels of paleo-rivers, ancient deltas	River mouth bars, furrows	*Relic*—paleovalles of the Pechora Sea, Laptev Sea, etc. *Modern*—outdeltas of Lena River
Jointly created by glacial covers and fluvial processes	Ice-marginal valleys and hollows of thawed snow flows, outwash plains, systems of eskers and kames	Absent	Shelves of the Norway and Greenland seas
Created or modified under industrial activity	Absent	Constructive positive forms of relief connected with ground spoil, artificial islands, the basements of port constructions, oil derricks, etc	Shelf of the Norway Sea, etc.
		Destructive artificial cuts and channels of ports, the river mouths, waterways in gulfs, etc.	Areas nearby marine ports within coastal shallow, etc.

Anadyr and Yukon rivers and with their discharge during the late glacial regression of the ocean (Carlson and Karl 1984). Modern fluvial accumulative forms of shelf relief are shallow locations of delta beaches proximal to the river mouth.

Conclusion

The modern state of coastal zones is the result of the interaction of complex processes within offshore, shoreline and offshore areas. Under ''coast'', we understand an ''onshore and coastal shallow that has been alternately flooded and exposed since middle Holocene time (climatic optimum).''

The classification offered here is based on scientifically proven representations of morphology, origin and age and geology. We call this kind of approach, which analyzes and determines a complex of interactive factors simultaneously, ''morphogenetic''.

Among the exogenic and endogenic processes involved, it is possible to allocate active processes, which directly participate in the formation of coastal relief, and passive processes, which predetermine the display of active ones and direct the course of their development. We have developed our understanding that the origin of relief (which formed under the interaction and combination of various modern or paleogeographical processes) is the main factor that created existing coastal morphology.

The development of coasts, their contemporary dynamics and their morphology are closely connected with the development of the offshore coastal zone. Therefore, the principles of coastal morphogenetic classification correspond to the principles of the morphogenetic classification of the Arctic coastal seabed and vice versa. Taking into account the indissoluble association of marine coasts with the coastal offshore, their joint mapping is possible with the use of a single procedure or approach, including one based on GIS technology.

The classification presented here is based on the general approach given in the ACD, which is a project of the International Arctic Science Committee and the International Permafrost Association (IASC Arctic Coastal Dynamics 2001). In addition to the morphological classification suggested by the ACD project, the classification suggested in the present paper considers interactions between coastal morphology and dominant factors (processes) governing coast formation.

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